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Using simulations to teach young students science concepts: An Experiential Learning theoretical analysis

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ABSTRACT

Early research investigated young students' understandings of science concepts using physical equipment, but technological advances now mean there are new options to introduce these ideas, through devices such as iPads and simulations. However, research investigating the use of simulations in early years' science learning is limited. This study applied revisions of Kolb's Experiential Learning theoretical model to determine if age-indicated science simulations were effective for teaching 5 year olds simple circuit building procedures and electricity concepts, and the function of circuit components. It also explored whether their engagement with the simulations provided worthwhile opportunities to exercise higher order capabilities such as reflective thinking and abstraction – skills oftencited in literature as valuable outcomes from older student and adult use of simulations. Findings indicate students developed a solid base of procedural knowledge about constructing different circuits, and functional knowledge about circuit components they applied to different circuit designs. The emergence of tentative, generalised theories about current and the effects of different circuit designs on the performance of resistors - linked to the exercise of reflective and descriptive thinking, were also noted in many students. However, examples were found of some simulations appearing to foster common misconceptions, such as current being 'consumed' by resistors – indicating teachers need to be highly vigilant and work closely with students, to ensure accurate understandings are developed. Overall, with appropriate teacher support and careful selection and review, the study concludes simulations can be effective for introducing young students to simple physical science concepts, and for providing them with opportunities to engage in higher order thinking processes.

1. Introduction

This article details results from a study involving a group of 38, 5-year old New Zealand primary school students using a range of simulations on iPads, to learn about simple circuit-building procedures and electricity concepts. The study investigated whether simulations, combined with strategic teacher guidance, were effective for introducing young students to simple circuit procedures and concepts, how circuit components functioned, and the extent to which simulations provided opportunities to exercise higher order capabilities such as reflective thinking and abstract conceptualisation. Applying revisions of Kolb's (1984) Experiential Learning theoretical model (ELT), it used screen and audio capture data to analyse students' interactions with each other and the simulations against revisions of Kolb's elements of Experience, Observation, Conceptualisation and Experimentation. Kolb's model provided a valuable lens for learning about how students built understandings of circuits from observations of events in the simulations, and from their interpretation of the simulations' responses to their actions, constructing tentative, explanatory theories about how and

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why circuits worked, as they did so.

While a number of studies have been undertaken with young students using simulations for mathematics learning (e.g., Bullock, Moyer-Packerman, Shumway, MacDonald & Watts, 2015; Rosen & Hoffman, 2009; Steen, Brooks & Lyon, 2006) and in special education (e.g., Bouck, Satsangi, Doughty & Courtney, 2014), it appears far fewer studies have been completed into their use in early years science learning. This study is relevant and timely, given the rapid increase in across-the-curriculum mobile device use in schools, calls to engage younger students in STEM-based inquiries and activities (e.g., National Research Council, 2011; Quinn & Bell, 2013; Vasquez, Sneider & Comer, 2013), and research suggesting value in using simulations to develop higher order thinking capabilities (e.g., Evagorou, Korfiatis, Nicolaou & Constantinou, 2009; Lieberman, Bates & So, 2009; Verenikina, Herrington, Peterson & Mantei, 2010).

2. Research questions

The research questions were:

1. Can science simulations help young students learn simple circuit concepts, construction procedures, and the function of circuit components?
2. Do science simulations provide opportunities for young students to exercise higher order capabilities, such as reflective thinking and abstract conceptualisation?

3. A review of literature

3.1. Young students' learning of circuit-building procedures and concepts

Studies dating from the early 1980s have investigated students' ideas about simple electrical circuits and their design, construction, and operation (e.g., Osborne, 1983; Shipstone, 1984). Although scarce, some more recent work has focused on younger students, specifically their capacity not only to construct simple circuits, but also offer explanations about how they work, and why operating circuits need to be constructed in particular ways. An interesting study by Glauert (2009) used predict, explain and explore methods to investigate 5 and 6 year olds' (n = 28) views on whether a bulb shown in photographs of different circuits, would be illuminated or not. They then tested their predictions using actual equipment. Results indicated that while most students successfully built an operating circuit (22/28), they struggled to offer scientific explanations of why their circuits worked, instead focusing on the components and connections that were needed to build the circuit. Interestingly, those students who correctly predicted operating circuits need to have two connections to the battery, were more able to offer tentative science explanations of why these circuits worked, than those who held 'single connection' ideas. Their explanations loosely-aligned with correct scientific thinking, such as the need for current to have a 'path', that is, "electricity goes round (sic) the wires" (Glauert, 2009, p. 1041), suggesting the emergence of "a dynamic view of electricity, and considering how it travels in a circuit" (Glauert, 2009, p. 1042). Glauert's results suggest that even very young students can form tentative theories about quite abstract science concepts, and that we should not underestimate their ability to do so. She commented that these understandings should be examined, and used to move students beyond basic procedural knowledge (the *how* and *what*), towards more complex conceptual knowledge (the *why*). She emphasised the important pedagogical role of the teacher in this process, by "encourage(ing) children to explain their thoughts and actions … and offer explanations that give insights into their developing thinking" (Glauert, 2009, p. 1044).

3.2. Using simulations for learning science concepts

A multi-database search (Sage, ScienceDirect, Emerald, BSP, Scopus, Wiley Online, T&F Online) revealed no singular, agreed-to definition of computer simulations. Instead, authors identified various attributes considered to be characteristics of simulations, including the ability to manipulate variables in a virtual environment (Wilson, 2016); form manipulable, computational representations of real or hypothesised situations or phenomena (Clark, Nelson, Sengupta & D'Angelo, 2009); provide a dynamic, interactive, visualised learning experience (Plass, Homer & Hayward, 2009) or in the case of science, comprise "computer-based animations (such as models, simulations and virtual experiments) of scientific phenomena" (Linn, Chang, Chiu, Zhang & McElhaney, 2011, p. 235). The search also returned very few studies involving young students using what were identified as simulations, in science learning. While using simulations in science is not new, most studies have involved secondary-aged students (e.g., Cohen, Eylon & Ganiel, 1982; Kolloffel & de Jong, 2013), teachers (e.g., Ates, 2005; Heywood & Parker, 1997) or college and university students (e.g., Aktan, 2012; Zacharia & de Jong, 2014).

The few studies that have been published involving younger students (6–12 years), suggest simulations *may* assist in learning fundamental science knowledge, including the physics of falling objects (Lazonder & Ehrenhard, 2014); evaporation and condensation (Wang & Tseng, 2018); and heat and temperature (Zacarias, Loizou & Papaevripidou, 2012). Wang and Tseng's (2018) study is particularly relevant, as it was one of the few studies found that used simulations with students close to the age of those in this research. Their quasi-experimental investigation involving 208 Taiwanese eight and nine year olds, compared the effectiveness of physical materials (laboratory), simulations, and a combination of both, for developing students' knowledge of the phase changes of water at a molecular level. ANCOVA analysis indicated statistically significant gains in 'scientifically-acceptable' knowledge for students who used the simulation either before the laboratory or by itself, compared with those who only completed the laboratory work. They concluded the simulation assisted knowledge-building by making abstract concepts more visible, and that generally, “primary school students can benefit from learning (science knowledge) through more than one representation” (Wang & Tseng, 2018, p. 216). This finding is consistent with similar studies involving older students (e.g., Jaakkola & Nurmi, 2008; Zacharias, Olympiou & Papaevripidou, 2008), suggesting benefits exist from using simulations in science learning. Of note, however, is that studies to date have all been undertaken using desktop computers in lab-like settings. Technology developments now mean educators have an array of touchscreen devices such as iPads, that could potentially better-assist younger students to understand science procedures and build science knowledge, through simulations more akin to manipulating physical objects. While little research has been completed in science, promising outcomes are emerging from studies of young students' use of touchscreen simulations for learning mathematics (e.g., Larkin, 2016; Moyer-Packenham, Shumway, Bullock & Tucker, 2015; Shin et al., 2017).

3.3. *Simulations and cognitive processes*

Research over a considerable period has highlighted the value of technology for supporting young students’ learning, “including conceptual and cognitive development, literacy skills, mathematics knowledge and competence, and comprehension monitoring” (Wang, Kinze, McGuire & Pan, 2010, p. 382). Wang et al. point to the multimedia capabilities of technology in early childhood learning that can “increase the representational richness of problems … (and) support cognitive and metacognitive processes” (2010, p. 382), specifically highlighting the value of simulations that allow students to easily manipulate objects (virtual manipulatives) creating new representations, carry out experiments to test hypotheses and tentative ideas, and assist in building awareness of personal thinking processes (metacognition). Iiyoshi, Hannafin and Wang (2005) claim young students are more likely to build new knowledge through multimedia representations that present or record information from different perspectives, and in different formats and modalities. Wang et al. (2010) align this with improving the “intellectual accessibility” (p. 383) of learning content, affording students greater opportunities to “reflect on, and recognize discrepancies in their own thinking, by allowing them to review their theories and compare those theories to others” (p. 384).

This perspective is supported by both early and more recent work that points to the capacity of simulations and educational games to form ‘virtual learning microworlds’, where students use embedded tools and resources to solve complex multidimensional problems, developing conceptual understandings, deductive reasoning, systems and computational thinking, abstract and reflective thinking, and advanced problem solving capabilities (e.g., Ainsworth, 2006; Evagorou, Korfiatis, Nicolaou & Constantinou, 2009; Fessakis, Gouli & Mavroudi, 2013; Flannery et al., 2013; Gros 2007; Squire, 2005; Verenikina, Herrington, Peterson & Mantei, 2010, Wild, 2011). The development of higher order capabilities through learner engagement with multimedia content is a relatively common theme in literature, but often in the context of game-based learning (Henderson, Klemes & Eshet, 2000). Although some conceptual work has theorised possible relationships between young students' engagement with digital games and simulations and cognitive outcomes (e.g., Gros, 2007), according to Henderson, Klemes and Eshet (2000), “there is little research related to outcomes of incorporating educational science simulations in early childhood education” (p. 106).

4. Theoretical framework

4.1. *Experiential Learning Theory (ELT)*

Experiential Learning Theory was used as the theoretical model for this study. Its focus on knowledge creation resulting from reflection *on* and *during* experience, and its acknowledgement of the importance of learning processes and not simply behavioural outcomes (Kolb, 1984), provided an appropriate lens through which to evaluate the efficacy of the simulations for supporting students' science learning, reflective thinking, and abstract conceptualisation (theory-building). ELT has its roots in early humanist theorising, particularly the work of John Dewey (1897) and Jean Piaget (1952). More recently, it has been conceptualised by Kolb (1984) as a process involving learners in an iterative cycle based on reflection, theory generation and knowledge application (experimentation), resulting from exposure to concrete experience. Kolb's original model comprised 4 stages: concrete experience, reflective observation, abstract conceptualisation and active experimentation. These are represented diagrammatically as a recursive cycle (Fig. 1), where a “learner ‘touches all bases’ – experiencing, reflecting, thinking and acting – in a recursive process that is sensitive to the learning situation and what is being learned” (Kolb & Kolb, 2012, p. 1216).

Concrete experience is described by Enns (1993) as “providing first hand exposure to the subject matter … personal, direct involvement in activities (that) often arouse initial reactions, intuitive impressions, and affective responses” (p. 9). During reflective observation, learners make meaning from their experience through observation and interpretation of events. To support this, Enns comments on the value of working in groups, particularly highlighting the value of discussion and dialogue for “sharing and brainstorming … (that) lend themselves to the deeper observation of issues enhanced through ‘what if’, rhetorical or reflective questions” (1993, p. 10). During abstract conceptualisation, learners form theories based on their interpretation of observed events, and the perceived relationships between them. They may link these to existing ideas, or form new ones from their observations. In the final stage, active experimentation, learners test their emerging theories, often in different contexts and scenarios. This stage serves as a “guide in creating new experiences” (Kolb, Boyatzis & Mainemelis, 2001, p. 228), and may act as a basis to confirm or modify emerging theoretical understandings.

Kolb's original concept was revised to provide a suitably-contextualised theoretical model for this study (Fig. 2). The original model has been supplemented by the addition of *Focusing* (Joplin, 1981), and expanded to include both reflective and descriptive thinking (see later). Joplin added Focusing, recognising the pedagogical application of ELT to classroom-based learning. She defines

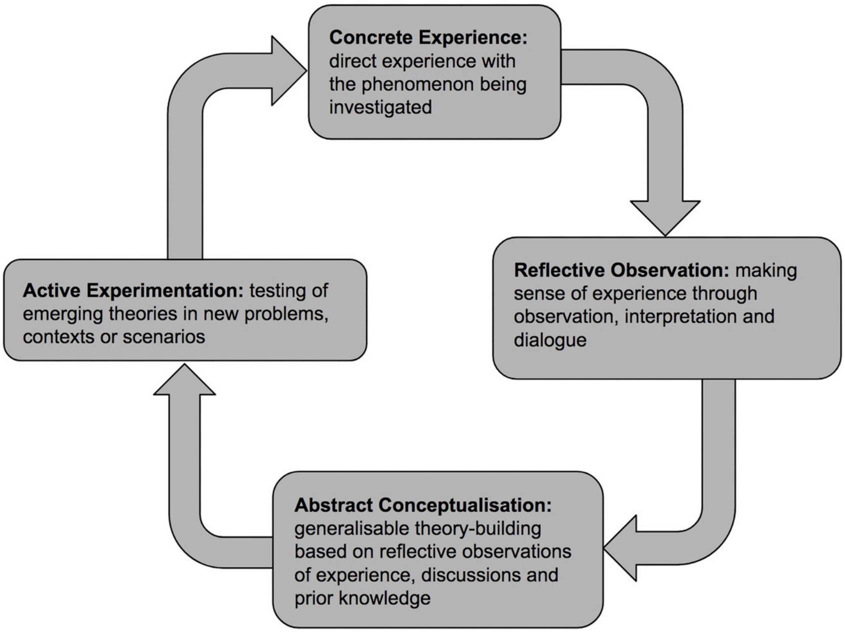


Fig. 1. Kolb's (1984) original ELT cyclic model.

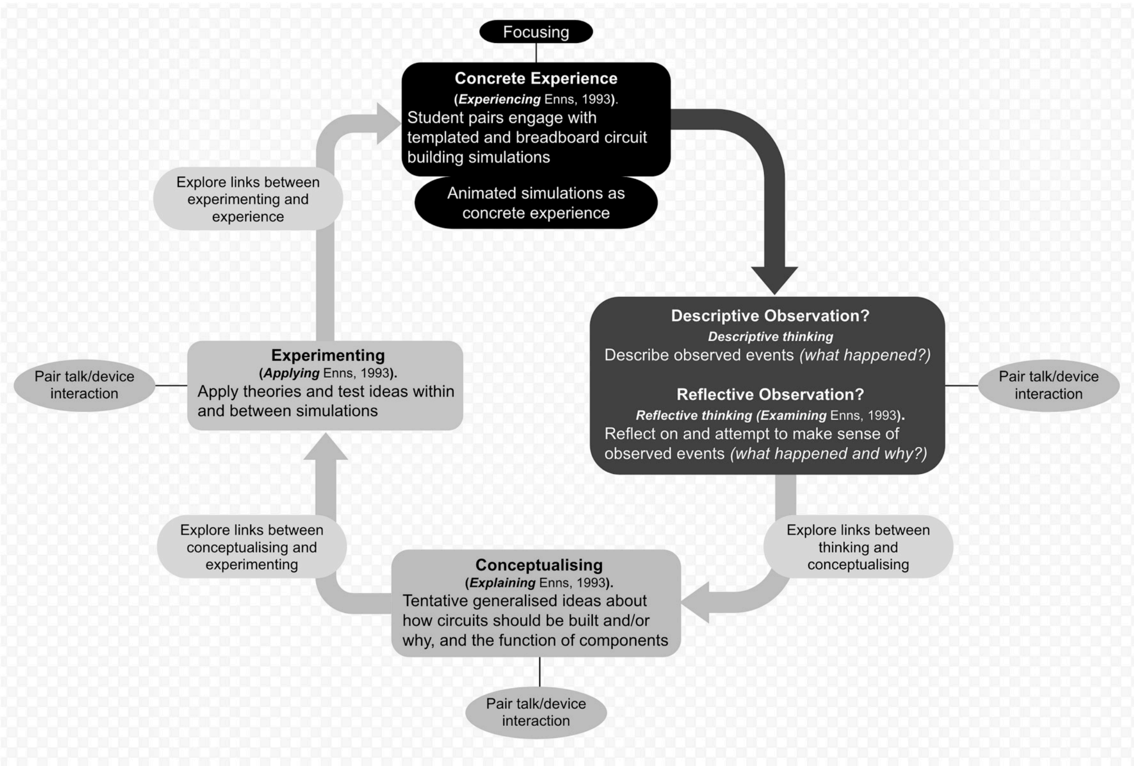


Fig. 2. The revised ELT model used in this study (from Kolb, 1984).

Focusing as "presenting the task and isolating the attention of the learner for concentration … (it is) specific enough to orient the student but not too specific so as to rule out unplanned learning" (Joplin, 1981, p. 18). The Focusing stage was compatible with the problem-based design (PB) and pedagogy of this learning unit. While the teachers provided an introduction to each lesson (Focus) and necessary learning support throughout the lessons, they did not engage in transmissive teaching of procedures or concepts. Indeed, literature on ELT suggests its incompatibility with such methods (e.g., Beaudin & Quick, 1995; Druian, Owens & Owen, 1995;

Joplin, 1981; Kolb & Kolb, 2012). Problem-based learning was compatible with ELT, and a frequently used pedagogical strategy in the research classroom.

Literature on ELT also notes challenges in reaching a singular definition of *concrete experience* (Beard & Wilson, 2006). However, there appears general agreement that it can take different forms but must contain some key elements: it must be meaningful, and allow learners "to engage with the experience and reflect on what happened, how it happened, and why" (Beard & Wilson, 2006, p. 20). In this study, *concrete experience* was conceptualised as students interacting with four, age-indicated app simulations, designed to introduce simple circuit-building procedures and electricity concepts.

5. Research context

5.1. Participants

Data collection occurred over a 4-week period in a large, flexible learning space in a semi-rural school in New Zealand. The participants were thirty-eight 5-year olds (20 girls and 18 boys) and three teachers. Most students had been at school for just over 3 months at the start of the study. The lead teacher, Sarah (pseudonyms used), had nearly 20 years experience teaching in junior classes, while the other teachers were Helen (5 years) and Rose (3 years). Sarah had been involved in previous studies in this research series (e.g., Falloon, 2013; 2015; 2016; 2017) while Helen and Rose were participating for the first time. No students had been involved in any previous research. The class's learning unit was entitled *Finding out about Electricity,* with 7, 30–40 min data collection points occurring during the unit.

5.2. Learning design and student organisation

Learning design followed a guided, problem-based learning (PBL) approach, using a series of 'Can You' challenge tasks (Fig. 3). The tasks were introduced by the teachers at the beginning of each lesson, and the student pairs were supported during lessons by teacher facilitation, principally:

- assistance with reading or interpreting challenge instructions;
- technical issues involving the simulations;
- open questions and prompts for students to review prior learning, help 'debug' non-operating circuits, and clarify emerging concepts;
- ensuring equitable student access to resources and learning opportunities.

Pairs were formed by the teachers based on their knowledge of the students' learning characteristics and behaviours, and their likely ability to work cooperatively. Notwithstanding absences on three occasions, the pairs remained constant during the lessons.

5.3. The simulations

Table 1 introduces the four simulations used by the students. The fourth simulation (Parallel Bulbs) was used by one pair as an extension task. The simulations were selected as they were all indicated as age appropriate (AppStore rated at 4+) and introduced basic circuit building procedures and concepts, including controlling current, current 'flow', series and parallel circuits, and voltage

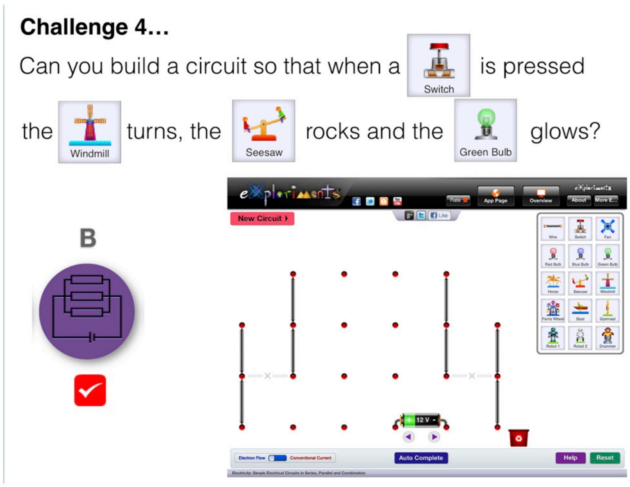
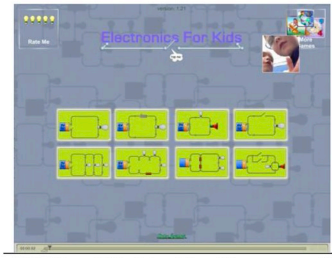
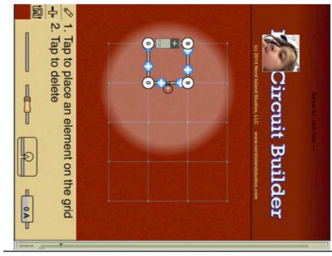
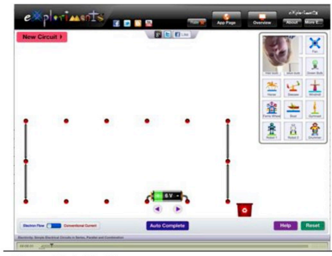
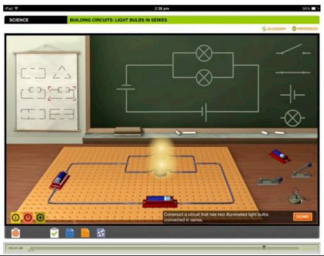


Fig. 3. A sample 'Can You' challenge task.

Table 1
The simulations used by the students.

Simulation	Description
Electronics for kids (AppStore age rating 4+) 	This was the first simulation introduced to the students. It comprised a series of circuit templates to be built with ‘drag and drop’ components. It included series and parallel circuits, and components such as switches, resistors, bulbs, cells and a siren. The simulation was selected as it introduced basic components (eg., switches, resistors, bulbs) and operational circuit attributes (eg., continuous current, no ‘gaps’, relative bulb brightness-series vs parallel etc.).
DC Circuit Builder (AppStore age rating 4+) 	This simulation is a breadboard design where circuit components could be connected using a ‘clip on’ grid. Components comprised wires, bulbs, a cell (fixed in place) and resistors. Current flow was indicated by moving electrons (blue +), and bulb intensity changed according to circuit (serial/parallel etc.). This simulation was selected as it required students to apply basic circuit design knowledge introduced by templates in simulation 1, in a more flexible environment.
Exploriments – Simple Circuits (AppStore age rating 4+) 	This simulation contained 2 modes. In ‘teaching’ mode, students were provided with a range of circuit plans (series, parallel, controlled, uncontrolled etc.) that contained different appliances (toys) and components (wires, bulb, switches etc.). They constructed these using the breadboard. In free-form mode, students were supplied only with breadboards (of varying complexities) and components (as in thumbnail). In this mode, students could build circuits of their own design. This simulation was selected as it introduced new appliances, more complex breadboards with multiple connection options, and supported variable voltage.
Parallel Bulbs (AppStore age rating 4+) 	This simulation was introduced to one pair only as an extension task. It contained similar components to the other simulations, but in a more realistic form (3D representations of components). Students could construct circuits either by dragging the components or the circuit symbols illustrated on the blackboard. Different circuit design challenges were illustrated on chart to the left of the board. A short text with voice over instructions introduced each circuit challenge. The instructions were complex, using specific technical terms that the young students using it found too difficult to understand.

and resistance. The simulations were introduced progressively, working from the templated format of Electronics for Kids, through to the open-format simulations Exploriments and Parallel Bulbs, where students designed their own circuits using virtual components and breadboards.

5.4. Data methods

Primary data were collected using a display and audio capture tool installed on 9 researcher-supplied iPads Airs. While 19 student pairs participated, licence restrictions meant only 9 devices could be equipped with the recorder. Recorded student pairs were selected by the lead teacher, using these criteria:

1. A mix of boy-boy, girl-girl, and boy-girl pairs;
2. Pairs of different abilities (blends of high, middle and low ability);

3. Known capacity to work co-operatively.

The recording tool ran in the background on each device, and captured as .mov files students' oral exchanges with each other and physical interactions with the simulations (e.g., finger placement, menu access, and optionally, Facecam recording). This data method has been used very successfully in past studies, in a range of different contexts (e.g., Falloon, 2016).

6. Data coding frameworks

6.1. Circuit concepts

The absence of empirical work with young students using simulations in this way meant a coding schedule needed to be developed from data. To facilitate this, the researcher and a science and engineering faculty member reviewed the simulations to determine the *main* circuit concepts they introduced. These were identified as:

- Operating circuits are closed (continuous current);
- Series circuits (voltage drop, resistors in single circuit);
- Parallel circuits (equal voltage, resistors in 'separate' circuits);
- Resistance in circuits (effect on current, resistor performance);
- Controlling current in circuits (circuit components).

The concepts were used as general 'marker codes' which were further defined into sub-codes to analyse the screen recordings for evidence of conceptual learning (Table 2). Data occurrences aligned with the codes were logged on Studiocode timelines (Fig. 4).

For coding, it was decided that conceptual learning decisions needed to include two forms of evidence: 1. the physical manipulation of components or appliances (wires, bulbs, switches, toys etc.) and 2. some associated verbal indication that the manipulation was deliberate (i.e., an explanation, comment or reason why an action was carried out). Requiring two forms of evidence added robustness to coding decisions by lessening the likelihood that students acted randomly or accidentally, or that occurrences were misinterpreted. A sixth concept, electron flow, was introduced using animated sprites in three simulations. Data related to electron flow were not coded separately, as they were infrequent and exclusively linked to other concepts (see Tables 6–10).

6.2. Thinking and conceptualising

A separate analysis was completed to identify the nature of students' thinking and conceptualising (theorising) from their engagement with, and observation of events in the simulations. The relationship between thinking and any explanatory ideas or theories about circuits and their components that emerged, and how thinking influenced students' pathways through the simulations, was also explored. Kolb's original model was extended to include both *reflective* and *descriptive* thinking, and related conceptualising. This resulted from a preliminary but detailed scan of data suggesting students tended to both *describe* and *reflect* on events, and it was later discovered that these different types of thinking often contributed to different complexities of theorising, different learning pathways, and qualitatively different learning outcomes. Full explanations of codes and illustrative samples of coded data are included in Table 3. Data occurrences were recorded on Studiocode timelines, as was done for conceptual learning.

6.3. Data sampling and coding

Nearly 31½ hours of display data were recorded from the 9 pairs. Due to financial constraints (the cost of RA support for blind coding) and the time-consuming nature of coding video data, a sample of just over 20 h were selected for coding. Selections were made to include at least one data sample from each pair, and to meet at least one of the criteria introduced previously. Studiocode software was used to code data, with separate coding templates being developed for conceptual learning, and thinking and conceptualising (e.g., Fig. 4). A research assistant (RA) familiar with Studiocode was employed to blind code a 5-h sample of selected data at the same time as the researcher. Conceptual learning decisions were based on 'single evidence' occurrences. However, if there was more than one occurrence in a single event (e.g., a discussion where 2 or more separate understandings were present), these were counted as multiple occurrences.

Results were compared and decisions debated, before common views of what each code 'looked like' in the data sub-sample were agreed upon. Occurrences where no agreement could be reached were discarded (Gwet, 2012). The RA then coded the remaining 15 h, while the researcher randomly selected 5 h of these data to use to perform reliability calculations. This exercise yielded good levels of rater-agreement, according to Landis and Koch's (1977) scales (Tables 4 and 5).

6.4. Findings

Agreed-to occurrence data were exported from Studiocode into Excel for analysis (e.g., Fig. 5).

Results for each were charted by main code only (Figs. 6 and 7). Sub-code data for Conceptual Learning were conflated into the 'parent' codes to simplify presentation. For Thinking and Conceptualising, stacked bars have been used to indicate the split between reflective and descriptive thinking, and conceptualising linked to each thinking type. Tables 6–10 provide data illustrative of coding

Table 2
Conceptual learning codes and descriptions.

Concept (code)	Circuit knowledge (sub-codes)	Indicative data from display recorder	Explanation of code (and students' responses) (NB: 'appliance' includes bulbs, toys etc.)
Operating circuits are closed (uninterrupted)	Circuits must be continuous	Circuit not working due to missing component/appliance	Operating circuits must be closed (**retrospective debugging** to locate fault usually caused by missing wire or appliance)
		Checking there are no gaps or spaces in circuit while building	Operating circuits must be closed (checking all components are included **while constructing,** not retrospective)
		Checking connections	Wires or appliances must be accurately connected (**retrospective debugging** connections when circuit doesn't work)
Series circuits (voltage drop, resistors in single circuit)	Current has only one path in a series circuit	Remove one appliance and others stop working	In a series circuit if one appliance is removed it creates a 'gap', stopping current to other appliances (**inserting or removing appliances** and commenting on effect)
		Ordering of appliances does not affect their performance	In a series circuit the order of appliances doesn't affect their performance (**changing order** of appliances and/or commenting on the **nil effect** of doing this)
	Appliances 'share' voltage in series circuits	All bulbs are dim	The more bulbs there are in a series circuit, the dimmer they will be (comments such as bulbs are **'dim'** or **'weak'**)
		All toys go slow	The more toys there are in a series circuit, the slower they will go (comments relating to **slowness** of **toys' actions**)
Parallel circuits (equal voltage, resistors in 'separate' circuits)	Current has more than one path in a parallel circuit	Remove one appliance and others keep working	In a parallel circuit, each appliance has its own current 'branch' (**inserting or removing appliances** and commenting on nil effect on others)
		'Laddering' appliances	Connecting appliances in a ladder-like formation **('piggy-backing' bulbs/appliances** by terminal-to-terminal connection)
	Appliances get the same voltage in a parallel circuit	All bulbs are bright	In a parallel circuit, all bulbs will be bright (comments such as all bulbs are **bright** and/or **'glowing circle' is the same size)**
		All toys go fast	In a parallel circuit, all toys 'go fast' (comments relating to '**equally fast speed**' of toys
Resistance (effect on current, resistor performance)	Resistance affects current	Bulbs change brightness	Variable (slider) and fixed resistor components affect appliance performance (comments relating to effect of **manipulating variable** or **including fixed resistor** on appliance performance)
Controlling current in circuits (circuit components)	Switches control current	Switches turn appliances on and off	Manipulating switches in circuits controls current to appliances (**opening and closing** switch and **noting effect** on **all** appliances)
		Switches can control different appliances in parallel circuits	Manipulating different switches in a parallel circuit can control current to separate appliances (**opening and closing** switch and **noting effect** on **individual** appliances)
		A master switch can control current to all appliances in a parallel circuit	A master switch can control current in a parallel circuit containing multiple appliances and switches (opening and closing **master switch** and **noting effect** on appliances, **regardless of state** of other switches)

decisions. The tables comprise data aligned with main circuit concepts and related sub-codes (indicated by bracketed, bold text), screenshots taken from the display recorder, and verbatim student audio. The coloured bolded text indicate data that were coded against the elements of the revised ELT model.

Italicised bracketed and bolded text has been used to highlight other occurrences of interest in data, such as the presence of 'consumption' misconceptions in Table 8, row 2 and Table 6, row 1, and early ideas about current flow (e.g., Table 9, row 3). It was interesting to note these in data given the young age of the students, and initial questioning that indicated they held very little prior knowledge about current. Conceptual data judged to align with more than one code – for example in Table 8, row 3, were included under both codes. The tables therefore comprise sample data from most pairs, illustrative of, but not exclusively aligned with each concept or element. Also, to aid clarity, not all occurrences in each sample are indicated in the tables.

7. Discussion of findings

The lack of other studies in this area with young students meant little was known about possible prior understandings these students may have held. This study's non-experimental design, the students' age, their short time at school and limited literacy capability, meant a pre-test method of determining prior understanding was rejected, in favour of a less formal approach of whole class questioning and discussion. Before the study commenced, lead teacher Sarah introduced the unit by asking a series of questions and prompts aimed at determining any prior knowledge the students held. The questions were open-ended, targeting knowledge of

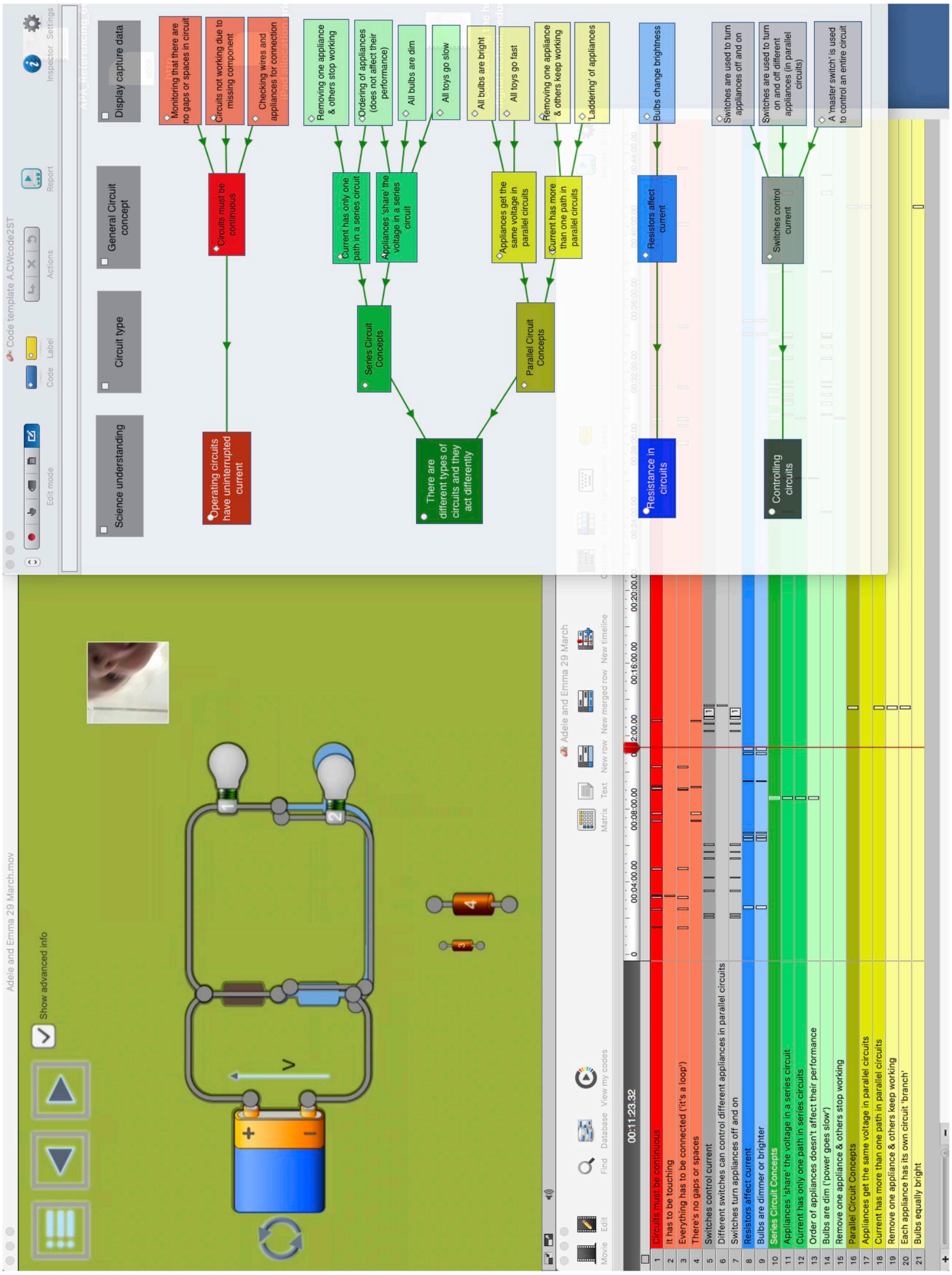


Fig. 4. Conceptual learning Studiocode timeline and code template.

Table 3
Experiential learning codes, descriptions and illustrative data (from Kolb, 1984).

ELT phase	Colour code	Description	Elaboration/illustrative data
Concrete experience	N/A	Introducing students to the tasks. Teacher-led ***focus*** activity.	Introduction to challenge tasks and simulations at the beginning of each session. Short revision of learning from prior session. Teacher support and facilitation during lessons.
Descriptive observation & thinking		Students ***describe*** observed events (what happened?) with no speculation/explanation of reason, or expressed intent to find out (why?).	Verbal description of simulation's response (or not) to students' input or action. "the energy bars (electrons) are going 'round (sic) the track" (J&P). "the power's going around… I can see it" (C&N).
Reflective observation & thinking		Students ***question*** observed events. Evidence of seeking explanation or reason, with explicit or implied reference to prior learning.	Verbal evidence of questioning result or seeking explanation (why?) "I wonder why all the energy bars are different?" (J&S). "It should be going… we did it like that before and it went" (L&A).
Conceptualising		Tentative ***generalised ideas or theories*** about how components function and/or how circuits should be built (procedures), and/or conceptual ideas or theories about why operating circuits need to be constructed in particular ways.	Verbal evidence or speculation indicating procedures and/or conceptual ideas about operating circuits. "You've got to connect them in a circle… like we did before…" (H&J). "Yep, it must be 'cos there's a gap… so the battery can't get through" (C&N). "The pump (switch) has to be down… it stops the charges… they can't get passed…" (B&E).
Experimenting		***Applying tentative theories*** and testing ideas within and between simulations.	Verbal and visual evidence of applying tentative theories and ideas within and between simulations. Direct reference, inference, or application of knowledge to solve problems in simulations. "…if we close this gate (switch) and the other one's still open… then the power should still go 'round… but if we open both gates, then it shouldn't" (J&S).

Table 4
Agreement calculations: conceptual learning.

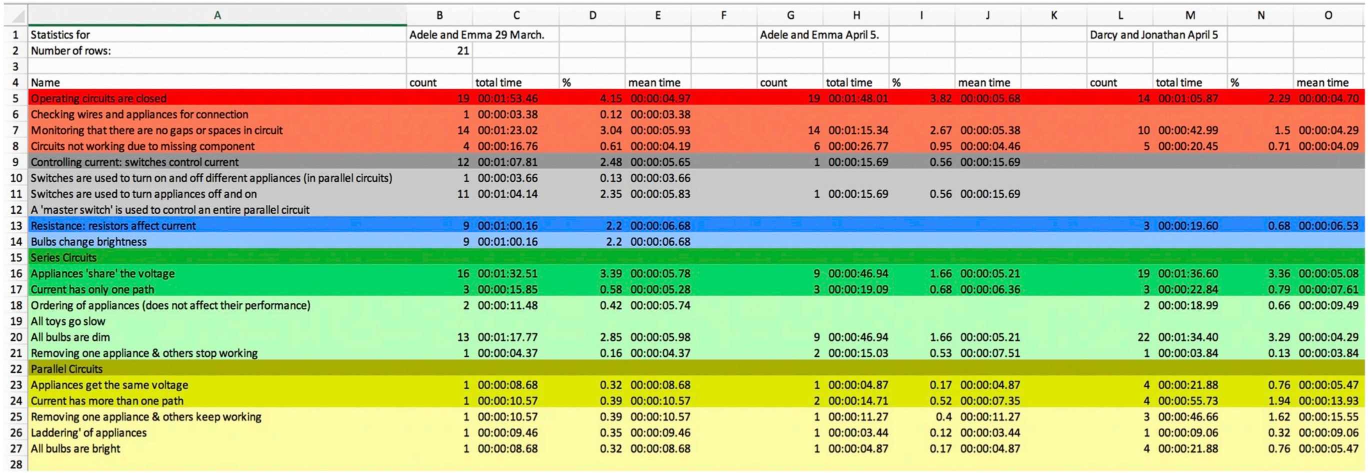
Concept	Number of occurrence agreements	Kappa (κ)	Std. error (SE)	Confidence interval	Agreement strength[a]
Operating circuits are closed (uninterrupted current)	186	0.666	.052	0.564–0.769	Good
Controlling current in circuits	87	0.690	.083	0.528–0.852	Good
Resistance	13	0.675	0.211	0.262–1.000	Good
Series circuits: appliances 'share' the voltage	76	0.629	0.120	0.395–.0864	Good
Series circuits: current has only one path	48	0.604	0.134	0.241–0.867	Good
Parallel circuits: appliances get the same voltage	37	0.706	0.185	0.343–1.000	Good
Parallel circuits: current has more than one path	26	0.727	0.247	0.242–1.000	Good

[a] According to Landis & Koch, 1977.

Table 5
Agreement calculations: experiential learning (from Kolb's elements of Experiential Learning).

Element	Number of observed agreements	Kappa (κ)	Std. error (SE)	Confidence interval	Agreement strength[a]
Reflective thinking from observations	111	0.662	0.075	0.516–0.809	Good
Descriptive thinking from observations	158	0.726	0.069	0.591–0.861	Good
Conceptualising	133	0.686	0.063	0.563–0.810	Good
Experimenting	112	0.779	0.060	0.660–0.897	Good

[a] According to Landis & Koch, 1977.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Statistics for	Adele and Emma 29 March.					Adele and Emma April 5.					Darcy and Jonathan April 5			
2	Number of rows:	21													
3															
4	Name	count	total time	%	mean time		count	total time	%	mean time		count	total time	%	mean time
5	Operating circuits are closed	19	00:01:53.46	4.15	00:00:04.97		19	00:01:48.01	3.82	00:00:05.68		14	00:01:05.87	2.29	00:00:04.70
6	Checking wires and appliances for connection	1	00:00:03.38	0.12	00:00:03.38										
7	Monitoring that there are no gaps or spaces in circuit	14	00:01:23.02	3.04	00:00:05.93		14	00:01:15.34	2.67	00:00:05.38		10	00:00:42.99	1.5	00:00:04.29
8	Circuits not working due to missing component	4	00:00:16.76	0.61	00:00:04.19		6	00:00:26.77	0.95	00:00:04.46		5	00:00:20.45	0.71	00:00:04.09
9	Controlling current: switches control current	12	00:01:07.81	2.48	00:00:05.65		1	00:00:15.69	0.56	00:00:15.69					
10	Switches are used to turn on and off different appliances (in parallel circuits)	1	00:00:03.66	0.13	00:00:03.66										
11	Switches are used to turn appliances off and on	11	00:01:04.14	2.35	00:00:05.83		1	00:00:15.69	0.56	00:00:15.69					
12	A 'master switch' is used to control an entire parallel circuit														
13	Resistance: resistors affect current	9	00:01:00.16	2.2	00:00:06.68							3	00:00:19.60	0.68	00:00:06.53
14	Bulbs change brightness	9	00:01:00.16	2.2	00:00:06.68										
15	Series Circuits														
16	Appliances 'share' the voltage	16	00:01:32.51	3.39	00:00:05.78		9	00:00:46.94	1.66	00:00:05.21		19	00:01:36.60	3.36	00:00:05.08
17	Current has only one path	3	00:00:15.85	0.58	00:00:05.28		3	00:00:19.09	0.68	00:00:06.36		3	00:00:22.84	0.79	00:00:07.61
18	Ordering of appliances (does not affect their performance)	2	00:00:11.48	0.42	00:00:05.74							2	00:00:18.99	0.66	00:00:09.49
19	All toys go slow														
20	All bulbs are dim	13	00:01:17.77	2.85	00:00:05.98		9	00:00:46.94	1.66	00:00:05.21		22	00:01:34.40	3.29	00:00:04.29
21	Removing one appliance & others stop working	1	00:00:04.37	0.16	00:00:04.37		2	00:00:15.03	0.53	00:00:07.51		1	00:00:03.84	0.13	00:00:03.84
22	Parallel Circuits														
23	Appliances get the same voltage	1	00:00:08.68	0.32	00:00:08.68		1	00:00:04.87	0.17	00:00:04.87		4	00:00:21.88	0.76	00:00:05.47
24	Current has more than one path	1	00:00:10.57	0.39	00:00:10.57		2	00:00:14.71	0.52	00:00:07.35		4	00:00:55.73	1.94	00:00:13.93
25	Removing one appliance & others keep working	1	00:00:10.57	0.39	00:00:10.57		1	00:00:11.27	0.4	00:00:11.27		3	00:00:46.66	1.62	00:00:15.55
26	Laddering' of appliances	1	00:00:09.46	0.35	00:00:09.46		1	00:00:03.44	0.12	00:00:03.44		1	00:00:09.06	0.32	00:00:09.06
27	All bulbs are bright	1	00:00:08.68	0.32	00:00:08.68		1	00:00:04.87	0.17	00:00:04.87		4	00:00:21.88	0.76	00:00:05.47
28															

Fig. 5. Excel Studiocode export for conceptual learning.

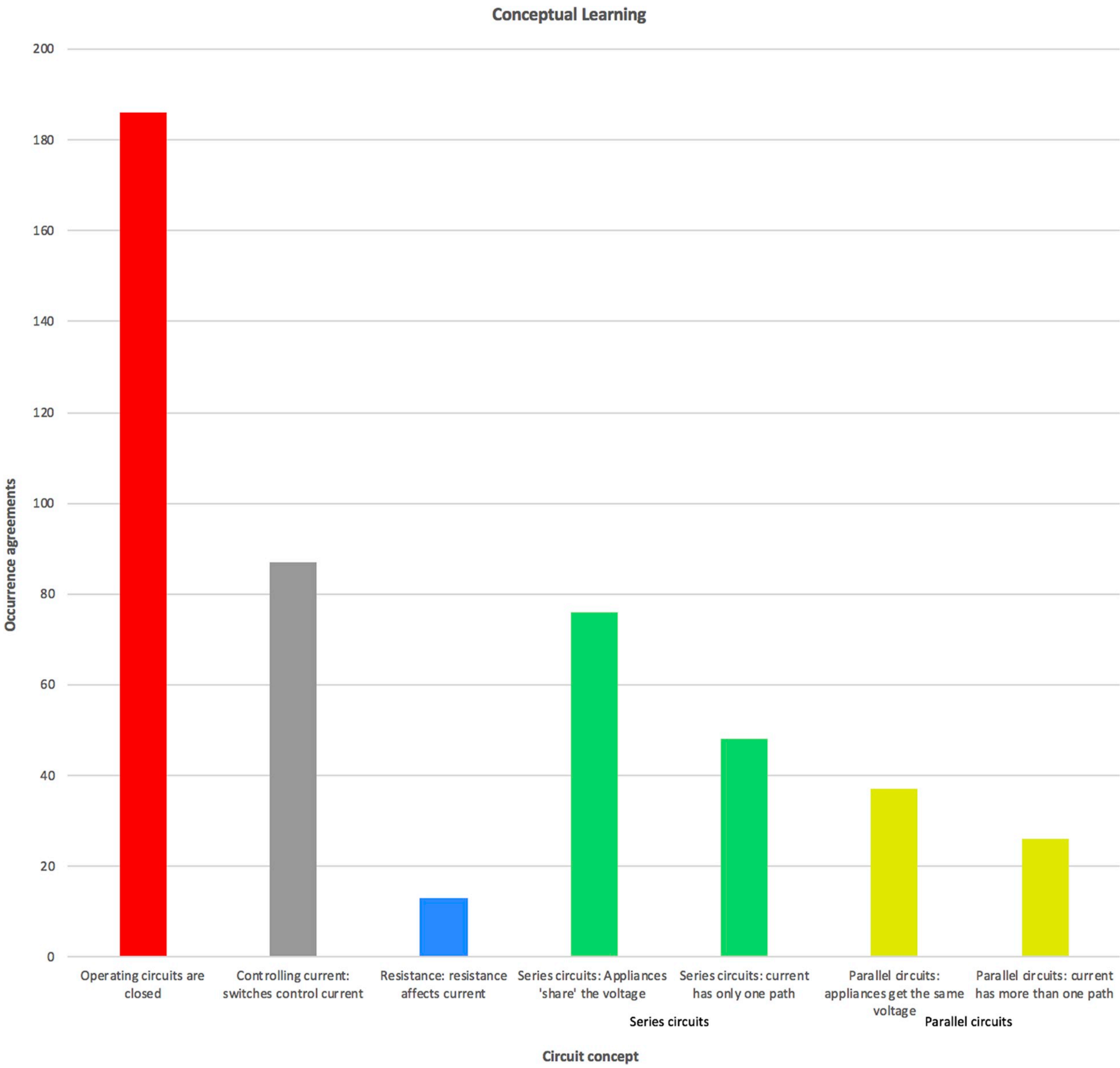


Fig. 6. Conceptual learning occurrences.

how appliances and devices such as lights and televisions work, and where they get 'energy' from. While students held some knowledge of electricity powering devices, Sarah reported,

> … most of them didn't have a clue … they knew about electricity, but thought the switch was where it came from … apart from Chris, whose … I think … his father is an electrician … he knew about wires in the walls.
>
> He'd seen it with his Dad's work … I suppose … and a couple of kids talked about the powerlines on the street and that they were dangerous, but that's about all …
>
> (Sarah, personal communication, July 27, 2017)

This exercise suggested the students held very limited prior knowledge of electricity and circuits.

1. Can science app simulations help young students learn simple circuit concepts, construction procedures, and how circuit components function?

Data indicates the simulations were effective for supporting students' basic procedural knowledge about constructing operating circuits of different designs, and for developing transferred functional understanding of different circuit components. Most prevalent

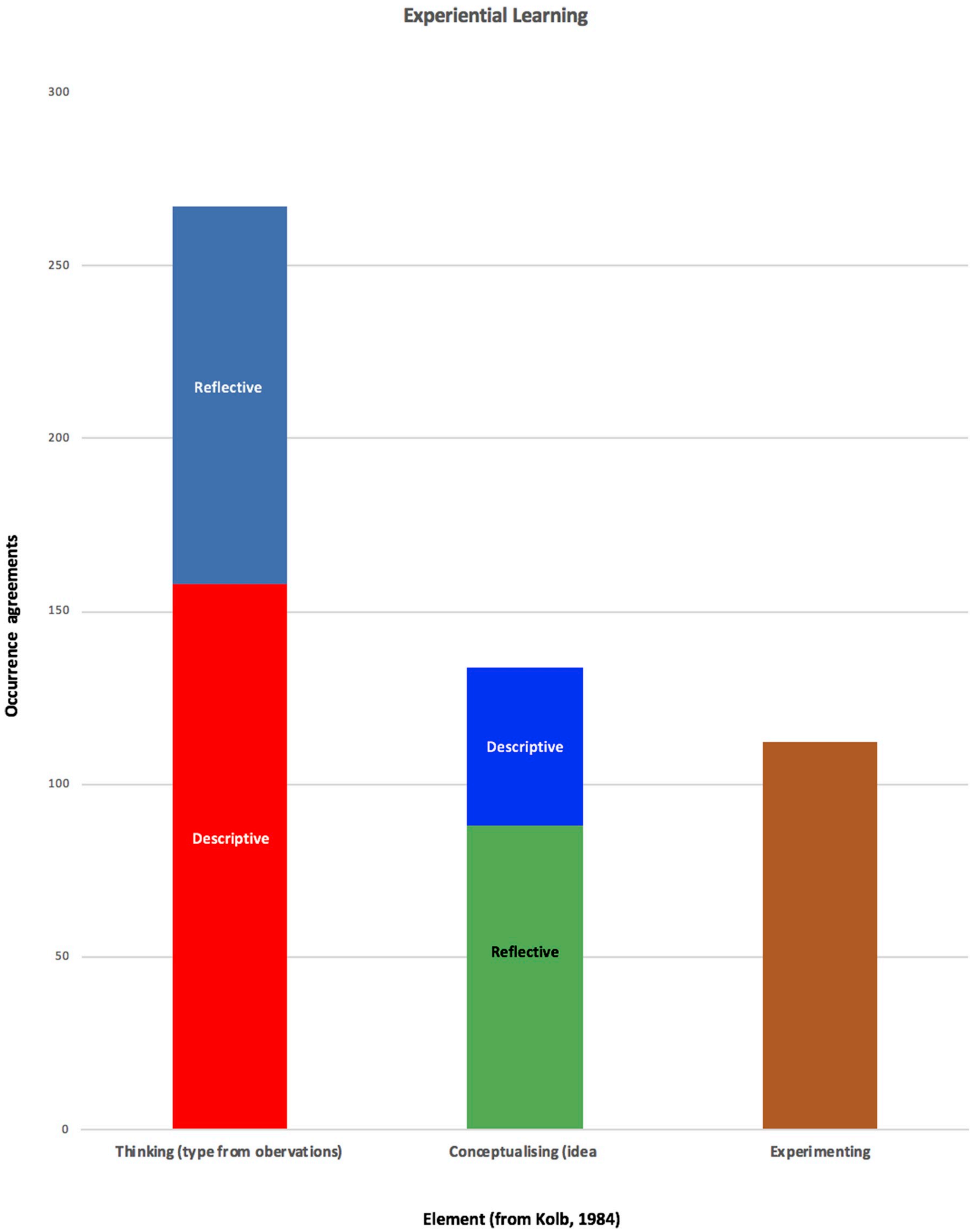
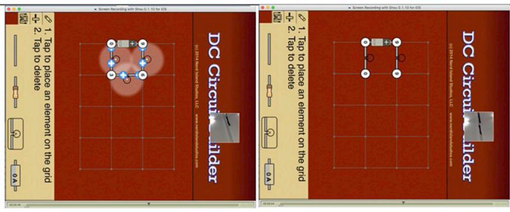
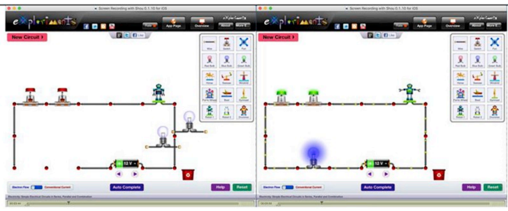
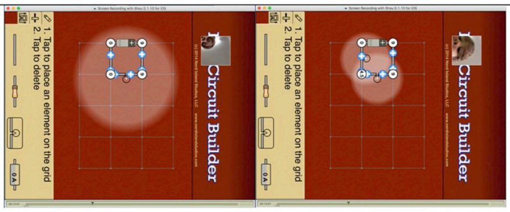


Fig. 7. Revised Experiential Learning model occurrences.

was knowledge about ensuring connections formed a closed 'loop' (186), and that switches were needed to control the operation of appliances (87). However, analysis suggests for most students this knowledge was built through observing, describing and then transferring construction techniques and component knowledge within and between simulations, rather than conceptual science ideas about the need for continuous current or how switches interrupt current, built from reflective thinking about *why* operating circuits must form closed loops. An example of this can be seen in Table 7, row 2, where student K directly transfers a successful technique used in a previous simulation, to solving a new problem in Circuit Builder – "we did it like that before … we can go down

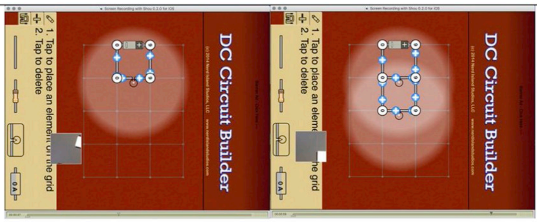
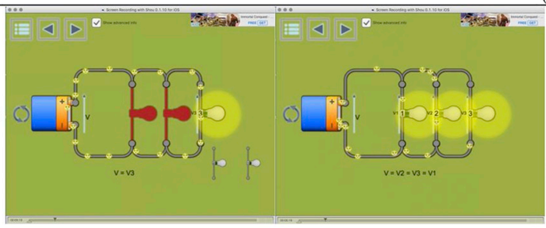
Table 6
Main concept: series circuits.

Main concept displayed (code)	Circuit knowledge (sub-codes)	Screenshot/s from display recorder	Audio transcript
Series Circuits	Current has only one path in a series circuit Removing one appliance and others stop working		Right… that's level 2 done… *(challenge 2)*… we've got 3 bulbs going… and they're not very bright (C)… *(first image)*… Yep… **the power's going around… I can see it...** *(pause)*… but it's *really* slow… (N)… **(circuits are closed)** …**maybe it's 'cos the bulbs are using it up** *(pause)*… (C)… (***series/consumption misconception***) … we need to take one out *(a bulb)* and see what happens (N)…. *(N removes end bulb)* It stops… *(pause)*… **is that what's supposed to happen?** (C)… *(second image)* **Yep… it must be 'cos there's a gap… so the battery can't get through…** we did it right (N)… **(circuits are closed/series)**
	Ordering of appliances does not affect their performance		What colour bulb was it again? (H)… *(pause)*… Um… *blue!* (N)… **OK… where do you want to put it? (H)… *(pause)*… *(first image)*…** **It shouldn't matter… as long as it's part of the fence… remember…** **(series)** (N)… *(pause)*… But shouldn't it be close to the battery? *(pause)*… it'll get more power…(H)… **No… it's no different... *(pause)*… they share the power, anyway…** **(series)** (N) OK… *(H drags blue bulb and wire to left of cell)*… *(pause)*… then we just have to turn it on… **(switches)** *(H taps switches)*… *(pause)*… look at the robot dancing (H)… *(laughs)*… Funny! *(laughs)*... and see… they both go… *(pause)*... the same power… **(series)** (N)… *(second image)*
	Appliances 'share' voltage in a series circuit All bulbs are dim		But we need *two* bulbs… it says so on the challenge (B)… *I know!*… *(pause)*… but remember the first one… we have to make it with one bulb, *first!*… we gotta (sic) see how bright it is (R)… *(pause)*… *(first image)*… *(R removes wire connected to – terminal and replaces it with second bulb)*… *(pause)*… *(second image)* **They're both duller… why's that?** (B)… *(pause)*… **Yeah… the circles are small**… *(pause)*… **maybe they're not getting as much (sic) charges…** (R)… **(series)**
	All toys go slow		*A and E had completed the circuit as shown, and had pressed both switches…***(switches)** **It's not very bright…** *(pause)*… **and the monkey's hardly moving… we must've done something wrong…** (A)… *(pause)*… *(first image)*… Monkeys can't play drums anyway! *(E, laughing, long pause)*… **Maybe he's not getting full power** (E)… **(series)** *(pause)*… ***E taps on the '+' arrow up to 30v (max). Bulb glows brightly and monkey speeds up*** *(second image)*… They've got more energy! *(A, laughing)*. **That's it… he's getting more power**… Super Monkey! *(E, laughing)*.

… see, we'll just put it here … just join it in … like before" (K&L). This conclusion is supported by the rapid drop off in the number of conceptual occurrences in simulations that embedded more complex concepts, such as those involving resistance or multiple-component parallel circuits.

Given the age of these students this finding could perhaps have been expected, however, not all students displayed this behaviour. Definite evidence existed that some were capable of reflecting on their observations or the simulations' responses to their input, and from that were able to generate tentative although sometimes speculative ideas and theories about why events occurred, occasionally offering explanations reasonably aligned with scientific thinking. An example of this can be seen in Table 8 in relation to switches controlling current. The dialogue between students J&S illustrates developing knowledge of how switches can 'channel', enable or prevent current flow. Although speculative, particularly interesting is J's emerging ideas about how multiple switches in a parallel circuit might control current to individual appliances (row 4, "maybe 'cos we can just turn one off"). Another example is seen in H&N's discussion about their series circuit in Table 6. N's comment about the positioning of appliances not being of concern "as long as its part of the fence, remember … because they share(ing) the power, anyway" (H&N, Table 6, row 2), indicates tentative ideas about voltage drop in series circuits. Although predictably scientific terminology was not used (series, voltage), the students did appear to

Table 7
Main concept: parallel circuits.

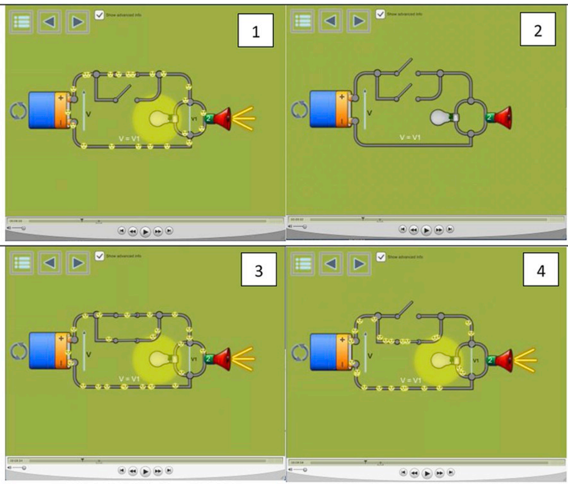
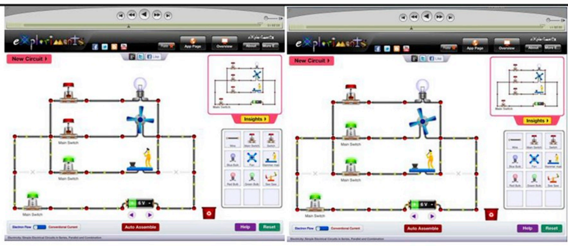
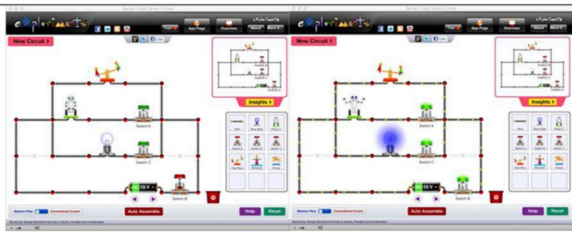
Main concept displayed (code)	Circuit knowledge (sub-codes)	Screenshot/s from display recorder	Audio transcript
Parallel circuits	Current has more than one path in a parallel circuit Removing one appliance and others keep working		We got 4 going… **I've never seen them *that* bright… have you, B?** (E)… *(pause)*… They're bright all right… but it said we only had to have 2 (B)… *(referring to challenge 2).* … **It looks like they're all getting full power in this one** (E)… *(pause)*… **(parallel)** *(first image)*… Yeah… they're all lined up**… maybe that's why?** **(parallel)**… *(pause)*… it says here that if we take out a bulb, the others need to keep going... is it right? (B)… *(pause)*… Umm… I'll find out! ***(E removes second bulb, image 2)***...**YES... it works… they still go**…! (E)… **The others must be getting power too**… **(parallel)** (B)… *(second image).*
	'Laddering' appliances		OK... what d'we have to do for challenge 2? (K)… Make a circuit with two bulbs glowing brightly, and when you take out one bulb, the other keeps glowing… *(pause)*… it says we can only use 4 wires *(L, reading)*… OK… *(long pause)*… maybe we can just put one on to this… we did it like that before *(referring to first challenge)* (K)… *(pause)*… **(parallel)** *(first image)*… Which way does it need to go? (L)… We can go down… see, we'll just put it here… just join it on… like before… (K) **(parallel)**. *(K adds second bulb, image 2)*… *(pause)*… *(second image)*… **Are they getting the same brightness?** (L)… *(pause)*… **I think so… the circle's the same size, anyway** (K)…
	Appliances get the same voltage in parallel circuits All bulbs are bright		… one bulb in… oh… *(pause)*… look… it's going already and we haven't even finished! (A)… *(pause)*… *(first image)*… We've made a line… they have to line up… **(parallel)**… **see, the charges are going 'round (electron flow)** (E)… *(pause)*… We have to put in 2 more… *(A drags bulbs 2 and 3 into place)*… Finished! (A)… *(long pause)*… **They've got the same brightness… it's right** (A)… *(pause)*… **(parallel)**… *(second image)*… **But where've the charges gone?** (E)… *(long pause)*… Umm… *(pause)*, **maybe the first one's used them up…** (A) ***(consumption misconception).***
	All toys go fast.		… just a few more wires and we've finished (D)… …come on D… we can't fail now… we've got to beat the challenge… *(pause)*… *come on!* (J)… *(first image)*… *(D completes circuit by adding wires. Toys move quickly and bulb glows brightly, second image)*… We did it D… *we beat the challenge!* (J)… Ha…ha… look at the seesaw… funny… they'll fall off! *(D, laughing)*… They go pretty fast… eh… **they must be getting lots of energy** (J)… *(pause)*… They're getting full power! (D) **(parallel).**

be forming general theories about performance effects of multiple appliances connected in a single loop, and that it makes no difference where appliances are positioned, relative to the power source. Similarly, early ideas about resistance were evident in other data (e.g., Table 10).

7.1. Simulation design and conceptual development

The design of simulations appeared to influence both procedural and conceptual development. Specifically, cognitive scaffolds built into some simulations such as animated sprites indicating current flow in wires and the 'snap-to' connector feature of two simulations, provided visible indications to students reinforcing knowledge of operating circuits as closed 'loops'. Stalled sprites provided students with a visual indication of a break or incorrect connection somewhere in their circuit, which often triggered checking for missing components or erroneous connections. In two simulations wires and appliances would snap in to place when close to a connection point, but the distance at which this was triggered, varied. For example, in *Electronics for Kids* the distance was approximately 10 mm, while in *Exploriments,* the distance was only 2–3 mm. Notably, significantly more occurrences coded under

Table 8
Main concept: Controlling current in circuits.

Concept (code)	Circuit knowledge (sub-codes)	Screenshot/s from display recorder	Audio transcript
Controlling current in circuits	Switches turn appliances on and off		*J&S had completed the circuit and were testing different switch combinations.* **…if we close this gate (switch) and the other one's still open… (*pause*)… then the power should still go 'round**…*(image 1)* **(switches)** *(long pause, tests)*… **but if we open both gates… then it shouldn't… (switches)** *(S opens both switches, image 2).* …OK… then… what happens if we close both gates? (J)… *(S closes both switches, long pause)*… **…oh… it goes both ways… see… it still goes 'round** *(S) (image 3)* **(parallel, switches)**…*(long pause)*… …it's got a choice (J)… *(pause)*… **(parallel)** but if we open the other one *(pause, image 4)*… then it doesn't… **(switches)**… *(pause)* …**it has to be shut to choose… (parallel)** (S)… *(pause)*… … it looks like a road with funny cars, eh! (J)… *(pause)*… Yeah! (S)… … **I wonder why the energy bars are all different?** (J)… **… maybe the light uses some up…** (S)… ***(consumption misconception)***
	Switches can control different appliances in parallel circuits		*A&I had completed the circuit (first image) and had turned on the lower main switch and switch 1. The hammer was moving.* Why isn't (sic) the other ones going? (I)… *(pause)*… Umm… the switch is on (A)… *(pause)*… … **but it's only the switch to the man… see… the other ones are turned off!** You need to press it (I)… **(parallel, switches)** *(A presses switch 2 and windmill turns, pause)*… **I get it… (*pause*)… there's a switch for each one** (A)…*(pause)*… **(parallel, switches)** Yeah… and **we need to have them down to make them go** (I)… **(switches)**
	A 'master switch' can control current to all appliances in a parallel circuit		*J&S had completed the circuit (first image) and had activated switches A and C.* It's not going… *(pause)*… we must have done something wrong (J)… *(long pause)*… Let me see… *(long pause)*… no… it looks OK… (S)… Ah… what've we done wrong then?… *(long pause)*… **I see… that switch's not down too… that one at the bottom… near the battery… d'we need that?** (J)… *(J presses switch B, all toys activate).* That one turns them all on… and off… on and off… *(J toggles switch B, pause…)* **(switches). Why d'we need the other ones then?** (S)… **…Maybe 'cos we can just turn one off** (J)… **(parallel, switches)**

'operating circuits are closed' were linked to *Exploriments* than to any other simulation, despite the fact that the time spent on each was similar. This possibly indicates the much-reduced tolerances in *Exploriments* were more effective for helping students understand the need for accurate connections, than the 'in-the-ballpark' design of *Electronics for Kids*.

While animated sprites were useful for helping students debug circuit connection issues, on the negative side, design errors in how they were represented in some simulations appeared to introduce students to misconceptions about what happens to current in circuits – specifically, current being 'consumed' by appliances. Some students interpreted the reduced number of sprites in wires when more appliances were present, as current having been 'used up'. Examples of this are in Table 7, row 3 and Table 8, row 2. Student dialogue in Table 7 strongly supports this conclusion, with student A speculating that E's observation of reduced 'charges' ("but where've the charges gone?") resulted from current being consumed ("maybe the first one's used them up …"). This outcome presents a dilemma for teachers. While these simulations effectively supported procedural and component knowledge and introduced related concepts by making the invisible, visible, design flaws increased the risk that the ideas students developed could be scientifically inaccurate. As earlier research identified (e.g., Osborne, 1983; Shipstone, 1984) once misconceptions are developed, they can be exceedingly difficult to dislodge.

Table 9
Main concept: operating circuits are closed.

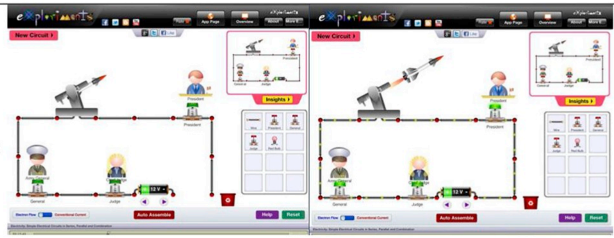
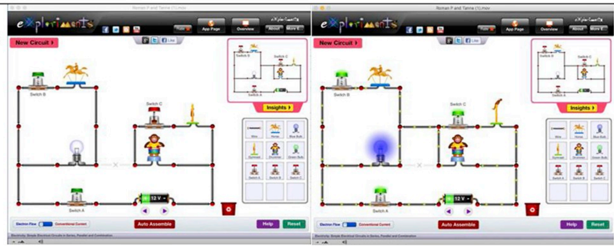
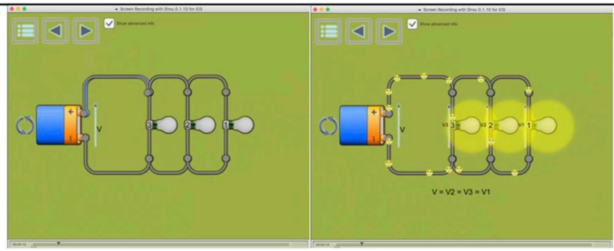
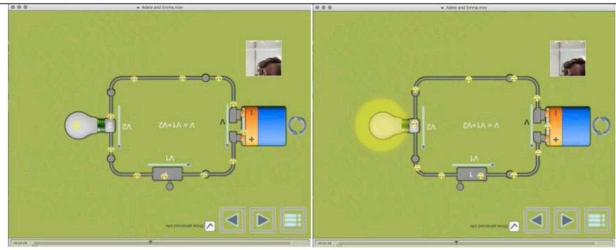
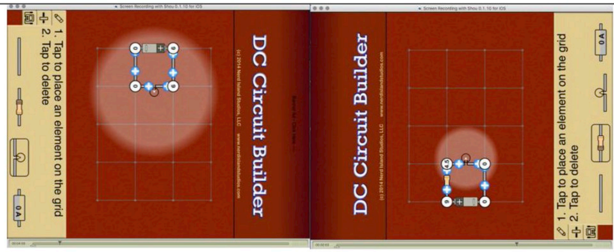
Main concept displayed (code)	Circuit knowledge (sub-codes)	Screenshot/s from display recorder	Audio transcript
Operating circuits are closed	Circuits must be continuous Circuits not working due to missing component		**Why's it not working?** I wanna (sic) see it blast off! (K)… *(first image)*… We've done something wrong… *(pause)*… ah… **the pumps (switches) are down**… um… (P)… *(pause)*… **(switches)** There's a wire missing… down there… see... **the energy can't get through**… (K)... **(closed)** *K positions wire, and missile launches (second image)*… WICKED!... Let's do it again! (P).
	Checking that there are no gaps or spaces in circuit while building it		There's 3 switches in this one… **why d'ya think there's so many switches?** (A)… Don't know… *(pause)* … maybe… **'cos there's lots of things in it…** (D). Don't forget to put one in here (a wire)… (A)… Where? (D)… By that switch… (indicating Switch C)… see… there's a space… (A)… **(closed)** …OK! (D)… *D drags a wire to close the circuit (image 2)*… **Why's the bouncer (gymnast) not going?** (D)… …Press the switch (Switch C)… remember before… turn it on… (A)…
	Checking connections		Finished (T)… *(long pause)*… *(first image)*… Ummm… what's happening? (S)… Nothing… *(pause)*… something's not working… let's see… **there must be a problem… they should be going**… (T) *(long pause)*… **I know… that wire isn't touching… see… it isn't touching the battery…** you need to move it so it's touching (S)… **(closed)** *T moves wire to connect with + terminal (image 2)… bulbs glow*… **You've gotta (sic) have it just right… eh, S… or else the power doesn't go through**… (T)… **(closed)**

Table 10
Main concept: resistance.

Main concept displayed (code)	Circuit knowledge (sub-codes)	Screenshot/s from display recorder	Audio transcript
Resistance in circuits	Resistors affect current Bulbs change brightness		*A&E had completed the templated circuit. This included a variable resistor (dimmer). They were sliding this back and forth and discussing the effect on bulb brightness.* Dim… bright… dim.. bright… dim… *(long pause)*… **I get it… the energy bars change… the switch must change them somehow (resistance)** (A)… What d'ya mean? (E)… Well, see… **when I move the switch it makes the light go up and down**… **it must be a special switch… (switches) it must do something to the energy (resistance)** (E)…
	Bulbs change brightness		*R&T had created a simple series circuit (image 1). Later, they explored other components (image 2).* I wonder what the sausage thing does? (R)… Try it! (T)… *(R adds fixed resistor to circuit in place of wire… long pause)*… OK… well… *(pause)*… that didn't do anything, really (T)… *(pause)*… **Yes it did… see… the power's going a lot slower that (sic) in the other one**… **(resistance)** *(pause)*…**and… look… the light isn't as bright... the circle's not so big** (R)… **The sausage must slow down the energy somehow** (T)… **(resistance).**

This appears to be an enduring issue with the design of so-called educational software. As far back as 2007, Gros, in her study of educational computer games, lamented that "game designers are not concerned with the accuracy of contents of the games, and on occasions, are capable of producing contradictions or erroneous concepts with respect to the function of games and learning activities" (p. 35). With increasing numbers of mobile-device based educational simulations being used in schools, developers should spend more time 'road testing' their products in classrooms, to get an accurate sense of how students of the targeted age range interpret and create understanding from them. Unfortunately, due to the nature of the app market built on the rapid development and high turn-over of low cost and often low quality apps, this is unlikely to happen. Teachers considering simulations would therefore be well-advised to scrutinise carefully how abstract concepts contained in them are represented, and be mindful of how these might be interpreted by their students.

2. Do science simulations provide opportunities for young students to exercise higher order capabilities, such as reflective thinking and abstract conceptualisation?

Illustrative data aligned with elements of the revised ELT model have been colour-coded in Tables 6–10. Descriptions of the elements and details of colour codes are included in Table 3.

Of the 269 events coded under the revised element of Observation, 158 were identified as students *describing* from observations (descriptive thinking), and 111 as students *reflecting* on observations (reflective thinking). Descriptive thinking generally resulted from students interacting with the simulations (e.g., inserting a component, activating a switch) and simply observing and describing what happened. Examples are in red text in Tables 6–10. Events identified as reflective thinking were more sophisticated, generally involving students either observing then questioning what happened – e.g., "but where have the charges gone?" (E, Table 7, row 3) and/or expressing a desire to find out e.g., "why d'we need the other ones then?" (S, Table 8, row 4). These events are coded in dull blue in the tables.

Data suggested a relationship existed between the type of thinking students' applied to their observations, their ability to conceptualise from them, and their subsequent pathway through the simulations. As shown in Fig. 7, relatively few events were coded as students developing generalised ideas about circuits or components from descriptive observations alone (45). While data coded in this way occasionally indicated a level of probable, although not necessarily accurate concept formation, this was generally speculative and based on descriptive rather than reflective observation. An example of this is in Table 9, row 2, when A&D were describing their observation of multiple switches in the circuit they were building. D's response to why this was - "don't know … maybe … 'cos there's lots of things in it", suggests understanding of a simple relationship existing between the number of appliances and the number of switches, rather than more scientifically-accurate ideas about different switches controlling current to different appliances. On the other hand, data coded as conceptualising from reflective thinking were different. In these events, students' ideas emerged from reflective observations, and were aligned with speculation or theorising about possible reasons or explanations for events. An excellent example of this is in Table 10 where E is discussing her observation about a variable resistor in their circuit, "… well, see … when I move the switch it makes the light go up and down … it must be a special switch … it must do something to the energy" (E, Table 10, row 1). In this illustration, clear links exist between E's reflective observations about the effect of sliding the 'special switch' (dimmer), and emerging science ideas about current and resistance.

Fig. 8 further revises Kolb's model by showing the generalised relationship between descriptive and reflective thinking and conceptualising, and the different pathways students took through the simulations. While examples of both descriptive and reflective thinking and to a much lesser extent conceptualising were present in data from all pairs, there was a tendency for students whose interaction with the simulations was more descriptive, to simply transfer or copy procedures or techniques from one simulation to the next (e.g., Table 7, E&B). While not exclusive, this tendency is shown in Fig. 8 by the 'bypass' arrow indicating direct procedural transfer from descriptive observations to the new simulation (experience). Conversely, students who displayed more reflective interaction tended to more readily translate this into conceptualising, and from there, to experimenting, where their tentative ideas were tested (e.g., Table 8, J&S). Again this was not exclusive, and some 'slippage' back to more procedural transfer was noted at each phase (indicated by narrow return arrows). Important to note, however, was that while the simulations triggered many students' reflective thinking, conceptualising and idea creation, and for some, provided a means to test their ideas, these processes did not necessarily lead to the formation of scientifically accurate understandings. As shown in the final phase of Fig. 8 (left upper quadrant), evidence was found of understandings that ranged from scientifically accurate through to misconceptions. The most obvious example of this found in multiple data was the emergence of current consumption misconceptions, that appeared to be introduced by students' interpretation of animations depicting current flow in some apps.

Theoretically, the revision of Kolb's model developed from this complex data analysis, illustrates the 'messiness' of these students' learning interactions with the simulations, challenging the systematic organisation of the original model. The orderly, cyclic nature of the original model has been critiqued in the past on the basis that it leads to "confusion over how these constructs (stages) relate to each other" (Bergsteiner, Avery & Neumann, 2010, p. 35). While Kolb's model was valuable to frame initial theorising from data, in its original form it was limited in its explanatory capacity to help understand the complexity of these young students' interactions with the simulations. As shown in Fig. 8 this process was complex and non-linear, with multiple pathways being pursued by students as they applied different observational and thinking skills to constructing and understanding their circuits. Mapping their pathways against the final revised model also highlighted how slippage or fading occurred between the different phases, as some students struggled to convert thinking and conceptualising into tested actions. These findings add some support to Bergsteiner et al.'s (2010) earlier critique.

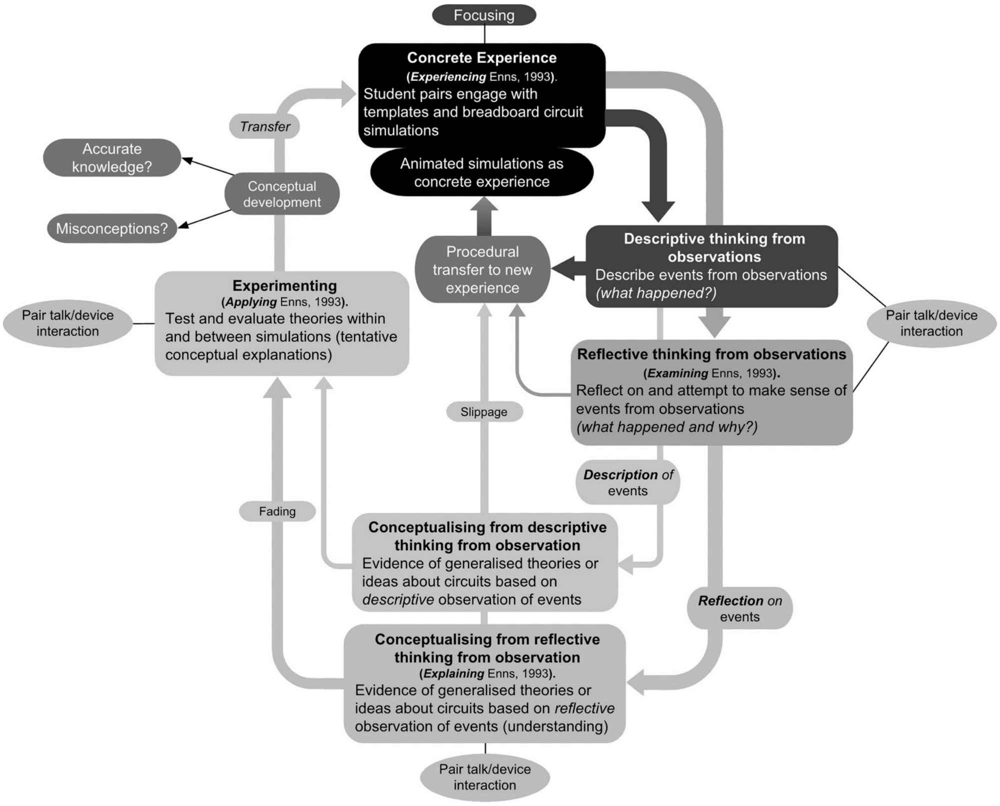


Fig. 8. ELT model indicating students' different interactional pathways.

8. Summary and conclusion

This study indicates the selected simulations effectively supported the young students' procedural knowledge related to building simple circuits, and transferred functional knowledge of what different circuit components do. They also provided the students with environments to exercise reflective thinking processes, that a significant number converted into tentative, generalised, conceptual ideas about how circuits worked and the attributes of operating circuits. However, it also highlighted that concepts students develop from simulations may not necessarily be accurate, especially when they introduce more abstract understandings. Although the selected simulations were all rated 4 + years in the App Store, it is likely this relates to operational capability rather than conceptual level. It may therefore be advisable for developers targeting this age group to clearly indicate this in their descriptive information, or simplify their designs by leaving out ‘bells and whistles’ features such as the animated current sprites, to minimise the chance of young students constructing erroneous concepts.

There are a number of important messages for teachers considering using simulations in their curriculum. First, it must be emphasised that while transmissive teaching was not a dominant strategy used in this study, this *did not* mean a ‘hands-off’ teacher role motivated by assumptions that all students, by themselves, would learn accurately from the simulations alone. As demonstrated here, this was not the case. All three teachers were fully engaged with the pairs during every session, challenging developing ideas with precise and targeted questions, and where detected, providing direct instruction to clarify emerging misconceptions. However, this study clearly illustrates that it is not possible for teachers to be everywhere all of the time, and that the accuracy of learning with simulations that occurs when teachers are not present and therefore unable to intervene, cannot be assumed. While the study found significant student benefits from using the simulations, it behoves teachers to be extremely vigilant with their use in group situations such as this. Further studies are needed to investigate optimal pedagogical models for using simulations in these scenarios.

Second, like selecting suitable resources to teach reading, it is important to consider not only whether students can technically operate the simulation, but that they can also understand the information and concepts it communicates. Using the reading analogy, while children may be able to read the words, this does not necessarily correspond to understanding the meaning behind the words. In appraising the suitability of simulations (or any ‘educational’ app for that matter), teachers need to evaluate their students' capacity to link conceptually to their content, and ensure that how concepts are represented or may be interpreted by students, minimises the chance of misconceptions.

Third, using physical science simulations with such young students amplified the importance of teachers possessing solid science conceptual understandings themselves, so they are in a good position to effectively guide students’ thinking towards scientifically correct knowledge. There were three teachers and 38 students in this very large teaching space, and while the teachers were diligent in working around the pairs, it was impossible for them to attend to each pair for more than a few minutes at a time. Well-developed open and deductive questioning skills, supported by a sound base of personal conceptual knowledge, were needed to ensure interactions were efficient, effective and accurate. In this sense, teachers should facilitate simulations in the same way they facilitate experiments with physical equipment, and not assume they are standalone resources.

Finally, while this study identified a number of considerations related to using simulations with young students, teachers should not view these as reasons not to use them. There were demonstrable benefits for students' thinking and conceptualising, and there was no doubt they found them motivating and engaging. Given the scarcity of junior school physical science teaching resources, they were effective for introducing students to science ideas and procedures they most probably wouldn't have been able to access in any other way. Considering current calls to engage students in STEM learning at a younger age, and past research indicating benefits from doing this, defensible arguments can be made for their stronger presence in early years' curriculum.

In closing, despite the proliferation of mobile devices and simulations in schools, it seems little empirical research has been completed with students of this age, working in normal classrooms. Many more studies of an exploratory nature are required to further validate, or challenge, the findings of this study. Of equal importance is that these studies should be undertaken in naturalistic classroom settings, where technology's performance is subject to the mediating effects of ‘at the chalkface’ student and teacher behaviour. While experimental or quasi-experimental studies in lab-like settings can provide certain information about potentials or possibilities, they frequently ignore the realities of making these happen in complex, demanding and multi-dimensional classroom settings. Notwithstanding this, and acknowledging obvious limitations to the generalisability of its results (this was not its purpose), it is hoped this study provides impetus for further research into how simulations might be better designed, and pedagogical approaches to using them for science learning - including optimal forms of teacher guidance, determined.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compedu.2019.03.001.

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